

AUG 19 1989

NAS 1.55: 3043

NASA Conference Publication 3043

mf - 0830 - H-10

(327)

Workshop on Two-Phase Fluid Behavior in a Space Environment

*Proceedings of a workshop held in
Ocean City, Maryland
June 13-14, 1988*

Workshop on Two-Phase Fluid Behavior in a Space Environment

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Proceedings of a workshop sponsored by the
National Aeronautics and Space Administration,
Washington, D.C., and held in
Ocean City, Maryland
June 13-14, 1988



National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Division

1989

ACKNOWLEDGEMENTS

This document addresses the results and observations generated at a national workshop on two-phase fluid behavior in a space environment. As such, it represents the combined efforts of all of the participants. The major technical contributors to this document included the Chairman, T. D. Swanson, the Co-Chairmen, A. Juhasz and W. R. Long, and the other Working Group Leaders; J. Acevedo, E. Coomes, W. Ellis, A. Fitzkee, R. McIntosh, T. Mroz, E. Ungar, and R. Vernon. L. Ottenstein made a significant contribution by analyzing the information generated at the workshop and in helping to prepare this document. The support and guidance of E. Van Landingham and M. Lopez-Tellado of NASA Headquarters, Code RP, is also gratefully acknowledged.

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EXECUTIVE SUMMARY

The trend in future spacecraft and space systems is towards ever-increasing size, complexity, and power consumption. The use of two-phase technology has been proposed to meet the increased requirements placed upon certain subsystems, such as thermal control, propulsion, power generation, and life support. However, the thermo-fluid dynamics of two-phase systems encompasses a wide range of complex phenomena that are not completely understood even in an "earth normal" gravity environment. The fundamental equations are quite complex and are often very difficult to solve. Empirical and/or mechanistic expressions are most often used for design purposes.

The partial gravity of space presents additional problems and a new challenge for engineering design. The validity of existing analytical expressions, almost all of which were developed for a normal gravity environment, is highly suspect. Although a limited amount of two-phase micro-gravity research has been performed and more is scheduled, there are still many more questions than answers.

This situation has resulted in the lack of reliable design guidelines for two-phase components and systems that are to be used in a space environment. A firm understanding of the fundamental laws of fluid mechanics is also needed. In response to these concerns, NASA Headquarters (Code RP), sponsored a workshop to bring together the nation's leading two-phase experts to discuss the above problems. This "Workshop on Two-Phase Fluid Behavior in a Space Environment" was held on June 13-14, 1988 at the Sheraton Fontainebleau Inn in Ocean City, Maryland.

The primary objective of this workshop was to identify and categorize/prioritize the major technical issues relating to the design of two-phase components and systems for space applications. Additionally, it was intended to identify fundamental fluid mechanic issues, determine the existing state-of-knowledge, and identify missing knowledge.

The workshop was conducted over a 2-day period. The majority of this time was spent in small working groups which were organized along technical lines. There were two sets of working groups. The first set considered the problems from a systems perspective. The second set of working groups focused on the actual two-phase phenomena of interest in certain subsystems or components. Each working group developed a consensus as to the major technical concerns within its area. In addition, the participants were asked to document their concerns on separate forms. In this way, the thoughts and observations of the participants were captured.

The workshop was very successful in achieving its main objective of identifying a large number of technical issues relating to the design of two-phase systems for space applications. The principal concern

expressed was the need for verified analytical tools that will allow an engineer to confidently design a system to a known degree of accuracy. New and improved materials, for such applications as thermal storage and heat transfer fluids, were also identified as major needs. In addition to these research efforts, a number of specific hardware needs were identified which will require development in the relatively near future. These include heat pumps, low weight radiators, advanced heat pipes, stability enhancement devices, high heat flux evaporators, and liquid/vapor separators.

One major observation resulting from the workshop is that a centralized source of reliable, up-to-date information on two-phase flow in a space environment would be of major benefit to the technical community. A limited amount of partial gravity information is available, but many researchers and designers are unaware of its existence.

Notwithstanding the currently available information, numerous technical issues remain. The great majority of designers will not trust the existing models until they have been verified with data from tests in micro-, partial, and/or artificially generated gravity fields. A variety of fluids also need to be tested. Hence, it is recommended that a coordinated test program be instituted to collect the appropriate information in a logical and efficient fashion. This test program should focus on the major design issues identified in the workshop and elsewhere. Fundamental concerns should also be addressed. The testing could be done with modular test fixtures. Ground testing should be emphasized with flight experiments performed only as needed. In order to contain costs, a specific phenomenon should generally be researched only to the level needed to obtain adequate resolution and experimental confidence. This test program is more fully discussed in Section 7 of this report.

The workshop participants indicated that they found the gathering to be a useful opportunity to discuss a complex and important subject. This is underscored by the fact that over two-thirds of the 150 people invited attended. In concert with the overwhelming majority of the participants, it is also recommended that another workshop be held in approximately one year. However, this and any other future workshops should be structured somewhat differently and have fewer participants.

1 INTRODUCTION AND BACKGROUND

In recent years, interest in the use of two-phase thermal control systems for space applications has increased considerably. For example, two-phase systems have been baselined for the Space Station. Traditional "passive" and single-phase technologies are considered unsuitable for such high power, long transport distance, multiple heat load applications. However, the thermo-fluid dynamics of two-phase systems encompasses a wide range of complex phenomena that are not completely understood even in a normal (i.e., Earth) gravity environment. The fundamental equations are quite complex and often very difficult, if not impossible, to solve. As a result, precise design tools do not exist and designers of two-phase systems are forced to perform a great deal of preliminary testing and/or overdesign in order to achieve acceptable risk. Designers generally rely on existing mechanistic and empirical models for design purposes.

The space environment, with its micro- to fractional gravity and hard vacuum conditions, presents additional problems and a new challenge for engineering design. Since almost all of the available analytical expressions were developed in normal gravity, their validity for space applications is quite suspect. A limited amount of two-phase micro-gravity research has been performed and more is scheduled, but there are still many more questions than answers.

As a result of this situation, there is a lack of reliable guidelines for designing two-phase components and systems for use in a space environment. A firm understanding of the fundamental laws of fluid mechanics is needed. In a reflection of this problem, NASA Headquarters recently received numerous proposals for two-phase flight experiments. However, due to both costs and manifesting constraints it is impossible to fly even a significant fraction of the proposed experiments. The concept of a coordinated testing program to generate the needed data has been proposed as a possible solution to this problem. However, the definite need, feasibility, and scope of such a test program remains to be determined.

2 WORKSHOP GOALS AND OBJECTIVES

In response to these concerns NASA Headquarters, Code RP, asked three field centers—Goddard Space Flight Center, Lewis Research Center, and Johnson Space Center—to organize and conduct a workshop in which the nation's leading two-phase experts could meet to discuss the problems mentioned above. This workshop was held on June 13-14, 1988 at the Sheraton Fontainebleau Inn in Ocean City, Maryland.

The workshop had several objectives relating to the design of two-phase thermal control systems for space applications. These were:

- to identify and categorize/prioritize the pertinent technical issues;
- to identify fundamental fluid mechanic and heat transfer issues;
- to define the existing state-of-knowledge; and
- to identify missing knowledge and determine the relative importance for acquisition of such knowledge.

This information is necessary in order to determine the need for, feasibility of, and scope of a coordinated test program. The focus of this test program would be to generate a generic data base of two-phase phenomena in a space environment that would be of sufficient scope and depth to be useful for most design purposes. The fundamental understanding, mechanistic and empirical correlations, and data thereby gained would reduce design risk and improve system optimization. In addition, the need for design-specific flight experiments would also be reduced.

Definition of a test program to accomplish the aforementioned objective requires considerable thought and planning. The workshop represented the principal activity in this planning process. It is important to note that definition of this test program was specifically not a goal of the workshop. Such a goal would be impossible for such a large group to effectively address.

3 WORKSHOP ORGANIZATION AND PROCEDURE

The workshop was conducted over 2 days. It began with a brief introduction and discussion of background and objectives. Next, a representative from NASA Headquarters discussed NASA's technology development plans and future missions which might involve two-phase technology. At this point the participants were split into smaller working groups. These working groups were intended to function as "brainstorming" groups in which a free exchange of concerns and ideas could occur.

Two separate sets of technical working groups were organized and conducted serially. The intent here was to provide the participants with an opportunity to look at the issues from different perspectives. The first set, which met in the morning of the first day, consisted of four groups which convened in parallel. These "Technology Application" groups provided a systems-level perspective. The four groups were:

- Thermal Control of Instruments and Equipment,
- Propulsion,

- Power Generation,
- Thermal Control of Life Support.

The second set of working groups focused on the actual two-phase phenomena of interest in certain major subsystems or components. These "Major Subsystem" groups thus provided a phenomenon based perspective which cut across the systems. They met in the afternoon of the first day and the morning of the second. To insure cross fertilization of ideas, each of these working groups had at least one member from each of the first set of working groups. The five Major Subsystem working groups were:

- Evaporation/Boiling and Condensation (cold plates, radiators, etc.)
- Thermal Storage
- Heat Pipes
- Compressors and Expanders (heat pumps, etc.)
- Applied Fluid Management (pumping, flow regimes, fuel cells, reservoirs, etc.)

Each of the nine working groups had a Group Leader. The Group Leaders began their sessions with a brief introductory overview of the problems in the working area. In most sessions there were presentations by the participants describing current work and/or providing viewpoints on the issues. All groups had a substantial amount of discussion. The Group Leaders or their assistants documented the issues and ideas generated. Participants were also asked to fill out forms describing their concerns and suggesting experiments to resolve them.

In the afternoon of the second day, the workshop participants reconvened as a single body. The Working Group Leaders summarized their groups' findings and recommendations. This activity concluded the workshop.

The workshop was very well attended by a broad spectrum of highly qualified researchers and engineers. Over one hundred people were present. About a third were from NASA, a third from industry, and a third from academia or the national laboratories. Most participants work primarily in the thermal control, fluids management, or power areas. Over half are engaged in applied research with almost all of the rest involved in either basic research or design. In general, the participants indicated that the workshop was an excellent and long overdue opportunity to meet and converse on this important subject area. However, a number of participants indicated that they were confused about the workshop goals. Despite the preliminary literature, some people seemed to have the impression that they were expected to propose tests in response to NASA's presentation of the issues. This misunderstanding reflects the difficulty in accurately communicating with such a large group. Appendix A presents a detailed breakout of the participants' professional profiles and their non-technical comments.

4 WORKING GROUP SUMMARIES

As discussed above, the workshop was organized into two sets of technical working groups. Each working group was intended to be a brainstorming session wherein the participants could freely discuss their perceptions of the issues and problems. Summarized below are the principal observations of each working group.

4.1 Thermal Control Of Instruments And Equipment

In reviewing the working group discussions and the submitted forms, the following major areas of concern were identified as requiring experiments or tests:

1. Development of a better data base associated with two-phase flow fundamentals at zero and variable gravity. This should include:
 - flow characteristics;
 - pressure drops;
 - heat transfer coefficients.
2. Improvements in computer codes for analysis of system performance and fundamental phenomena.
3. Investigations of the influence of tubes, valves, fittings, bends, etc., on two-phase flow pressure drops and flow patterns.

The major system problems to be explored include:

1. System instabilities generated by variable heat loads and variable gravity.
2. System control and fluid management.
3. Fundamental fluid mechanics and system designs applicable to thermal control of high heat flux.

The working group discussion also addressed the potential applicability of existing nuclear industry two-phase flow work, as well as many of the recurring themes identified below.

4.2 Propulsion

The major system components in propulsion are propellant handling, the engine or thruster, and the interface and controls. As a fluids issue, the propellant handling system is of most importance. The requirements of this system include:

- A means of storing the propellant;
- An acquisition method;
- Fluid transfer; and
- A method of providing positive phase control.

The working group identified the following technical issues or major problems:

1. Liquid-vapor interface—being able to define and control it.
2. Positive phase control throughout the fluid handling system.
3. Thermal management for cryogenic or warm fluids.

The system components or operations affected by these problems include:

- system venting and/or filling
- fluid acquisition
- mass gauging
- net positive suction head (NPSH) for pumps
- fluid transfer
- long-term storage

The discussions also addressed the designer/researcher interface and the need for having design considerations drive research priorities.

4.3 Power Systems

The major components in a power generation system include the following:

- Heat sources, including nuclear, solar, and chemical.
- Power conversion systems (PCS), such as Alkali Metal Thermoelectric Conversion (ANTEC), Brayton, Rankine, Stirling, Thermoelectric, Thermionic, and Photovoltaic.
- Heat rejection systems. These consist of radiators and associated heat exchangers. The radiators may be based on a variety of concepts including pumped loop, heat pipe (with a wide range of working fluids), LDR/LSR (liquid droplet/sheet radiator—advanced concepts that are not affected by micro-gravity but may be affected by atomic oxygen in the space environment), and moving belt radiator concepts (MBR). Micrometeoroids and space debris are a concern.

Particular concerns pertaining to specific systems or subsystems include:

1. Solar dynamic systems are affected by void formation on freezing of the thermal storage material used in solar heat receivers. The thermal storage material is needed to assure a constant heat supply to the power conversion system during the shade portion of the orbit. A more detailed discussion of this problem is included in Section 4.6.
2. For the Brayton power conversion system, the heat pipe radiator transport duct may carry a cycle working fluid which experiences a 200- to 300-K temperature drop. For this application, it will be necessary to have a radiator with several heat rejection zones, each of which would use a different set of heat pipes. The working fluids for these heat pipes may range from potassium or cesium at the hot side of the radiator to water or ammonia for the cold side heat pipes. For this wide range of working fluids, the operating characteristics in a space environment need to be understood.

Higher temperature heat pipes using sodium or lithium as a working fluid would be used to supply heat to a power conversion cycle. Containment of these alkali metal fluids will be a challenge.

3. In a thermoelectric nuclear system, using lithium as a coolant, one problem is that the liquid lithium cooling loop is subject to radioactive decay which produces helium. The helium must be removed from the cooling loop or the cooling performance will degrade. Similarly, non-condensable gas removal devices will also be needed for Rankine or ANTEC systems.

In one suggested system, the "swirl vane" concept, an artificial gravity field is produced to overcome the micro-gravity effects, and a wick structure is used to contain the helium.

4. For Rankine and ANTEC power conversion systems, liquid-vapor separation in micro-gravity is a serious concern.

The information generated by the Power Systems working group included preliminary summaries, which permit drawing the following general conclusions.

Much advance testing and analytical code development work can be accomplished prior to on-orbit testing, with few exceptions. The analytical codes need to be capable of modeling not only micro-gravity fluid behavior, but also the effect of body forces due to artificially induced force fields in a continuously variable manner. This will permit simulation of micro-gravity, partial gravity, and multi-g effects, and thus will lead to increased understanding and insight into the fundamental phenomena. Also, artificially induced forces, such as centrifugal, capillary, magnetic, electrostatic, osmotic, and others could be analytically evaluated as to their effectiveness in substituting for the missing g field in various space subsystem

applications. Modeling efforts will also have to include long-term effects of space environmental hazards such as micrometeoroids, debris, atomic oxygen and space plasma. Major subsystems that will require eventual validation and proof testing in orbit were identified to include the following:

- Rotating fluid management devices of the type proposed for Rankine and possibly alkali metal thermoelectric (AMTEC) power conversion systems. Such devices could also be used in general applications where liquid/vapor separation is required.
- Devices using capillary action and surface tension forces to control liquid flow. Typical applications and examples are heat pipes, liquid control in propellant tanks, and an alternate method of achieving liquid return in AMTEC power converters.
- Swirl vane liquid/vapor separators for nuclear systems with liquid lithium primary cooling loop where radioactive decay of lithium to helium leads to non-condensable gas entrainment.
- Thermal energy storage devices where void formation and void location during freezing of a phase change material (PCM) is a concern requiring resolution.
- Space radiators using pumped loop, heat pipes, or advanced concepts such as liquid droplet/sheet or belt radiators. Transition from nucleate to film boiling in a micro-g environment was judged to be an issue affecting heat pipe operation.

There was a general consensus that more communication between basic researchers, system designers, and the user community is needed. Furthermore, in aiming for high reliability for systems with low accessibility for maintenance, design complexity should be kept to a minimum. In the same vein, autonomous operation and fault-tolerant designs were recommended.

4.4 Life Support

The major issues identified by the life support working group included a need for:

1. Non-toxic, non-flammable two-phase heat transport fluids for manned environments. Relevant factors include:
 - Toxicity and flammability requirements and guidelines.
 - Definition of the level of "acceptable" toxicity. This definition may vary with the use of the fluid. For example, the toxicity specification for plant compartment fluids could be less stringent than the specification for crew compartment

fluids because of the limited time spent by the crew in the plant compartment.

- Consideration of other types of fluids including azeotropes, multi-fluid mixtures, and water additives (that increase vapor pressure and decrease freezing temperature).

Micro-gravity data on processes involving the selected fluids will be required.

2. Heat rejection in low-temperature manned environments, including plant compartments. Comments in this area include:

- Heat pumps may be required to reduce radiator area for low temperature heat rejection systems.
- Consider that heat pumps may be integrated into the heat transport circuit.
- Reduced gravity condensation/evaporation data applicable to heat pumps may be required.
- Mid-temperature (150 to 250 degrees C) heat pipe development is needed, including fluid evaluation and reduced gravity testing.
- Bubble membrane radiator concept data for condensation on large surfaces in reduced gravity should be studied.
- The liquid droplet radiator concept needs evaluation in a micro-gravity environment.

3. Investigation of low gravity effects (i.e., other than micro-gravity) on heat transfer processes, including:

- Lunar and Mars gravity fields;
- artificial gravity fields required for manned compartments; and
- data on processes in the range of 0- to 0.6-g including fluid dynamics, boiling, and condensation.

4. Plant compartment thermal requirements.

5. Evaluation of two-phase quality sensors in a reduced gravity environment.

6. A clearinghouse for two-phase analytical tools, including experimental data supporting design correlations.

4.5 Evaporators, Boilers, And Condensers

The issues of high importance related to components in this area were identified by the working group as follows:

1. Capillary-controlled evaporators
 - dryout and recovery from dryout;
2. Flow boilers
 - stability (including the effects of enhanced surfaces),
 - critical heat flux or departure from nucleate boiling,
 - pressure drop;
3. Capillary-controlled condensers
 - wick designs and geometries,
 - recovery from flooding;
4. Shear-controlled condensers
 - interfacial stability,
 - convection coefficient.

The following general topics were identified by the working group as important and applicable to all components:

1. Stability of liquid/vapor interface in flow, from the viewpoint of heat transfer and fluid mechanics.
2. Distribution of phases/flow regimes. For example, in an evaporator or condenser, it is important to keep the liquid in contact with the wall. The processes are not well understood for micro-gravity.
3. Thermodynamic properties of alternate working fluids.
4. Types of working fluids. High priority should be given to non-metals and multi-component mixtures; consideration should also be given to metals and cryogens.

Some general conclusions were also identified. These included the need to link researchers and designers, and the need for a coordinated test program. This program was viewed by the working group as an ongoing, iterative process between theoretical work, experimental work, and the design process which would result in the continued development and improvement of design correlations. It is imperative that these correlations include the appropriate scaling parameters (dimensionless groups).

Testing must be performed to determine if a continuum exists from 0 to 1-g and to greater than 1-g. Where such a continuum exists, tests will not have to be performed at all appropriate gravity levels. In any case, the proportion of ground-based testing must be maximized. This includes 1-g, drop tower, Learjet, and KC-135 tests.

4.6 Thermal Storage

The function of thermal storage is to store sufficient thermal energy at a specific temperature for use in:

1. Solar dynamic power systems for use in shade portions of orbits.
2. Systems/experiments requiring high quality vapor.
3. Other applications yet to be defined.

The types of thermal energy storage include latent heat and sensible heat. Candidate materials include eutectics (such as LiF-CaF_2), salts (such as LiF), and metals (such as Li and Ge). The thermal energy selection criteria parameters include heat of fusion, melting temperature, density, thermal conductivity, heat capacity, containment material compatibility, and chemical/thermal stability.

The working group concluded that experiments are needed to verify heat transfer rates in micro-gravity to a thermal energy storage medium in the presence of voids. Thermal energy storage materials characteristically expand in converting from solid to liquid. In the case of LiF , the expansion is as high as 30 percent. As an example of an application, when high temperature surfaces (as high as 900 K to 1400 K due to concentrated solar flux) are considered, with orbit cycles of 35-50 minutes in sun and 35 minutes in shade, the cavity in the heat receiver is hit almost instantaneously with a very high heat flux. This requires a high conductivity thermal energy storage material to prevent cycling and failure. The related technical issues include:

1. Geometrical influence on voids—the geometry of the heat receiver where the void is contained.
2. Void formation, size, and movement.
3. Kinetics of phase change.
4. Melt and freeze patterns.
5. Thermo-physical properties such as thermal conductivity, specific heat, and density.

6. Containment material. If this is not compatible with the storage material, the interface properties are likely to change after a few thousand hours.

7. Surface properties.

The flight experiments should be based on need-driven technology and should not be focused on merely generating a data base. However, these experiments should incorporate the outputs of both fundamental studies and relevant previous experiments. The working group also advocated continued communication between researchers and designers and improved correlation of analytical and experimental work.

4.7 Heat Pipes

The heat pipe working group focused on the need for micro-gravity data in support of future missions. It addressed the broad range of operating temperatures from cryogenic to liquid metal and considered various types of heat pipes needed to control the temperatures of components, subsystems, instruments, and spacecraft. Areas discussed by the working group included:

1. Cryogenic pipes. Requirements are arising in sensor cooling and focal plane cooling applications. There have been only a few flights of ethane and methane pipes, and no significant work in the liquid nitrogen temperature range and below. If good micro-gravity data can be obtained in the liquid nitrogen range, the designers would be comfortable in extending the results to the hydrogen or helium range.
2. Large area, composite wick pipes. Monogroove, tapered artery, side flow, and other large artery pipes are being considered for Space Station applications. It was determined that the work being done for Space Station will provide sufficient data for this class of pipes.
3. Heat pipes operating in an intermediate temperature range (100-250 degrees C). Examples of applications include power systems. Water is the most prominent fluid of choice and there are issues such as freezing, thawing, and restart after thawing where few micro-gravity experiments have been performed.
4. The Marangoni problem—a surface tension related phenomenon that occurs in liquid systems and can impact the large area, composite wick systems. This was not regarded as a significant problem requiring separate attention and could be combined with other related efforts.

5. Gas/liquid management in both cryogenic and liquid metal heat pipes where they are overfilled to permit operation over a wide temperature range.
6. Artery priming and start-up from the supercritical state in cryogenic heat pipes.
7. Micrometeoroid/debris penetration problems. These were system-related concerns that were discussed. Existing models and efforts in this area were judged adequate for heat pipe design.
8. Liquid metal heat pipes. A variety of liquid metal pipes will be needed for space power conversion systems.
9. Analytical models. The models will require verification for micro-gravity, but are sufficient for engineering applications.
10. Variable gravity—for lunar or artificial gravity applications.

The following micro-gravity data requirements were identified:

For cryogenic pipes—

- Startup from the supercritical state
- Heat flux limits
- Nucleate/film boiling
- Transport on the ground
- Artery priming
- Inertial effects.

For water pipes—

- Freeze/thaw
- Startup
- Nucleate/film boiling
- Artery priming.

For liquid metal pipes—

- Startup from the frozen state
- Heat flux limits
- Pulse response
- Volume density questions
- Shutdown
- Artery priming.

The cryogenic data will be needed in 2 to 3 years. Priorities depend on applications.

Liquid metal pipes have not been flown. It was felt that a useful and workable approach would be to start with water pipes (that have many of the same concerns) and work up to the higher temperatures associated with liquid metals.

4.8 Compressors And Expanders

The major focus of the compressors and expanders working group was in the area of heat pumps. Categories of heat pumps include mechanical vapor compression, absorption, adsorption, magnetic, Stirling, and other.

The working group had the following general observations.

1. Many design concerns unique to heat pumps do not appear to be particularly gravity-dependent and can be ground tested. However, a significant amount of research and development needs to be done to develop space qualified hardware.
2. Numerous design problems do exist.
3. The nature of the application drives the relative criticality of issues.

The problems and concerns were categorized by the working group and presented in order of criticality. The problems and concerns are as follows.

Major issues; highly critical:

1. Heat transfer rates in machine components are unknown in micro-gravity, especially for evaporation and condensation.
2. Fluid flow through valves, fittings, and manifolds is unknown. Instabilities and pressure drop are a concern.
3. There is a lack of analytical design tools that are verified for micro-gravity. It may be necessary to design around instabilities or to conduct tests of point designs.
4. The selection of operating fluid/material is a major design driver. However, the properties of many materials are unknown. In some cases, there is data at specific design points, but there is a lack of adequate theory to extrapolate the data for performance predictions as a function of changing environment.

Important issues; critical, but not necessarily enabling:

1. Decontamination and functioning of traps;

2. Fluid management;
3. Long life and reliability;
4. Safety for the manned environment;
5. Suitability for servicing by robotics and interfacing to expert systems and AI;
6. Materials of construction for high temperature applications; and
7. Vibration isolation for precision optics.

Other issues; moderate importance:

1. Optimal cycles by application;
2. Efficiency/weight/serviceability tradeoffs;
3. Leak detection and isolation;
4. Instrumentation (such as quality sensors);
5. Low temperature materials of construction;
6. Controls; and
7. Vibration and isolation.

4.9 Fluid Management

The initial scope of this working group included the following:

1. Two-phase fluid flow concerns in reduced gravity—
 - Fluid flow regimes
 - Associated pressure drop
 - Analytical modeling
 - Two-phase fluid pumping;
2. Positioning of two-phase fluids in reduced gravity—
 - Accumulators and reservoirs
 - Fuel cells.

There was a general dichotomy between those who believe that enough is known about two-phase fluid behavior in micro-gravity to design a system, and those who believe that very little is known about the basic phenomena.

Two topics were added to the scope during the discussions:

1. Pressure drop in straight adiabatic flow lines. Some participants thought that this would be insignificant compared to pressure drops incurred elsewhere in the system, e.g., in fittings. Others felt that every item of information can be useful in developing an understanding of the governing principles for two-phase flow in micro-gravity.
2. The issue of whether testing is required. Some participants were of the opinion that a system should be overdesigned to guarantee successful operation, and later optimized or improved. The contrasting argument raises the question of how to determine that a system is overdesigned and to measure the amount of overdesign without actually testing the system.

Technology issues identified by the working group included:

1. Fluid management/positioning in reservoirs, tanks, and accumulators—
 - Fluid positioning by capillary forces
 - Sloshing effects
 - Mixing and bubble formation
 - Convection in bulk phase and heat and mass transfer at the liquid/vapor interface.
2. Two-phase flow pressure drop/flow regimes—
 - Capillary-controlled flow
 - Buoyancy-dominated flow (in reduced gravity)
 - Inertia-dominated flow
 - Transition of stratified to annular flow for varying gravity levels
 - Effects of oscillatory forces on structural integrity
 - Transient and acceleration impacts.
3. Two-phase flow in bends, fittings, valves, etc.
4. Miscellaneous—
 - Two-phase flow behavior in partial gravity field generated by centrifugal force
 - Measurement of evaporator demand
 - Long-term operation of two-phase systems.
5. A small number of participants felt that in-space experimentation is not essential to successful development of working hardware.

The working group identified that ground-based tests should be used to address these issues as much as possible. Space-based testing,

because of cost and time constraints, should be used only in appropriate situations.

Design of fluid management systems is a process that is complicated by g-jitter, heat and mass transfer across the liquid/vapor interface, solid/liquid/vapor contact angles, etc. The best approach may be to try different configurations of baffles in different tank sizes/geometries to gain experience that could be applied to individual designs. In general, there is little of a generic nature that could be tested, but experiments can provide information regarding geometries that will work under particular situations.

The test article designed for liquid/vapor positioning could be used for experiments focused in other fluid management areas such as the time taken to move liquid, issues of mixing (vapor and liquid), and heat transfer.

The working group also agreed on a proposed approach involving a modular two-phase test article that could be used interchangeably on the Shuttle, the Space Station, aircraft (e.g., KC-135), or in a thermal vacuum chamber. It would be in the form of a generalized thermal bus system except for the capability for switching evaporators, condensers, pumps, accumulators, reservoirs, and possibly for accommodating different working fluids and for operating over different temperature ranges.

The working group agreed on the need for close cooperation between researchers and designers. Also, there is much information available in the literature for one-g applications, but it is difficult to apply to the design of space-based systems.

5 RESULTS

5.1 Technical Issues

The workshop was a major success in identifying the technical concerns relating to the design of two-phase systems for space applications. As is evident in Section 4 above, the working group discussions were wide ranging and addressed a large number of topics. Many issues were identified and discussed at some length.

In addition to identifying issues in the working groups, the participants were asked to fill out "Technical Issue" forms which further detailed their thoughts and concerns. A total of 147 issue sheets were submitted. The sheer number and scope of the issues identified demonstrates the participants' consensus that serious concerns exist regarding design of two-phase systems for space applications. These forms also asked the participants to address criticality and technological readiness. However, this additional information proved more difficult to solicit. Only about half of the

forms submitted had an assigned criticality while substantially fewer indicated technological readiness. The reasons for such omissions are unclear.

Both the group discussions and the Technical Issue forms reflected a broad range of technical issues and concerns. Hence, it is difficult to statistically develop a short and simple summary list. Establishing a prioritization is even more difficult. However, there do appear to be some general themes which were either implied or explicitly stated either in the working groups or on the Technical Issue forms (or both). These can be separated into two categories: research and hardware needs. The basic and applied research needs identified by this workshop include:

- two-phase instability identification and characterization;
- improved analytical models based on fundamental laws;
- determination of relevant material and fluid properties; and
- development of better mechanistic and/or empirical models for use as design tools.

The single most common concern expressed was the need for better and more accurate two-phase flow information and design tools. The range of new information requested was broad. Prominent was the desire for a better means of predicting both pressure drop and heat transfer coefficients for a variety of fluids in different gravity fields (micro, partial, and artificial). Numerous participants also indicated that these models should be sophisticated enough to account for bends, valves, sudden constrictions or expansions, etc. Various types of tests—from drop tower, to aircraft, to Shuttle, to Space Station—were suggested to develop and confirm these mechanistic and/or empirical correlations.

In addition to two-phase flow concerns, there appears to be a need for better models of the thermal storage freeze/thaw cycle. People working in the power and thermal storage areas were concerned about the freeze/thaw behavior of materials, particularly with regard to the formation of voids during freezing.

The need for a better knowledge of materials and fluids properties was cited for a number of technologies including heat pipes, thermal storage, and heat pumps. Participants in the life support area indicated a need to identify and/or develop a non-toxic, two-phase working fluid. This task is complicated by the problem of first defining just what a non-toxic fluid is.

Flow instabilities and the conditions responsible for the initiation of instabilities were cited as a concern by a number of people. Indeed, some participants even expressed the thought that the need to design around instabilities will be the major driver in systems

design. Determination and control of the liquid/vapor interface was also identified as a major concern by several people.

In addition to the research needs discussed above, the participants identified a number of hardware needs requiring development in the relatively near future. Many of the hardware needs represented solutions to generic problems. The primary hardware needs identified were:

- Heat pumps
- Lightweight radiators (e.g., 5 kg/m² or less)
- Advanced heat pipes
 - cryogenic
 - upper mid-temperature (e.g., water)
 - high temperature
- Improved materials (e.g., high strength to weight ratio, greater corrosion resistance, higher temperature tolerance, etc.)
- Stability enhancement devices
- High heat flux evaporators
- Liquid/vapor separators.

Additional discussion of the above hardware concerns and their justification is presented in Section 4. Again, prioritization of these principal issues is very difficult.

Appendix B presents a detailed analysis of the 147 technology issue forms received. In reviewing this analysis it should be understood that it represents an assemblage of individual comments and does not necessarily reflect the group view. However, the same general observations are present.

5.2 Recurring Themes

Several general issues or themes seemed to be common to a number of sessions. These issues were independent of the technical focus of the working groups and deserve to be reported separately. They include the following:

1. A limited amount of information on two-phase flow in a space environment is available, but many designers are unaware of its existence. Most of this information is in the research literature. However, many details relating to design are missing.

2. In the past decade, mechanistic models for two-phase flow have been developed by the nuclear, chemical, and oil/gas industries. These models may also be very useful for aerospace applications. In fact, these models may become simpler when applied to a micro-gravity environment since gravity will no longer be a factor. However, the models will definitely change since the influence of the buoyancy terms will become smaller while that of the surface tension terms will become larger. Unfortunately, most current models ignore surface tension effects. Therefore, their suitability for space applications is questionable.
3. A compilation of the existing knowledge into a single coherent data base would be of major benefit to a wide variety of people. This data base should be continuously updated as new data becomes available. It should include actual performance data, mechanistic and empirical models, and perhaps a set of guidelines for designing two-phase thermal control systems.
4. Transients, instabilities, and fluid positioning (both knowledge and control) will probably be major design drivers. These issues are often the most difficult to deal with analytically.
5. Most of the micro-gravity data collected to date has addressed idealized, simple situations (such as adiabatic flow through a pipe) that generally do not reflect a substantial portion of any real system. This is understandable since the study of such phenomena is in its infancy. Actual hardware will include much more complex flow, such as that through valves and fittings. Although more difficult to analyze, such situations are nevertheless more of a design driver.
6. Designers can be expected to continue to press for hard, design specific data because i) they are unfamiliar with two-phase phenomena in general, ii) their experience has told them to expect surprises in space, iii) it is difficult to effect a repair in space, and iv) the impact of a failure on life support, cost, and schedule can be great. Hence, a high degree of confidence is needed.
7. There is a clear need for better communication between system designers and academic researchers. NASA-funded research should be focused to reduce the uncertainties that have a major design impact. Unfortunately, the problems that are of prime academic interest are often relatively easy to work around in design, while a modest reduction in other uncertainties (that are of little academic interest) can result in major design benefits.

8. Although space is largely characterized by micro-gravity conditions, there exists a need for consideration of a variety of gravity fields. These include gravity that is artificially generated by rotation, partial gravity at lunar and planetary surfaces, and accelerations during maneuvers. These different gravity fields increase the difficulty of ground testing.
9. Despite the preliminary background information and introductory speech, it proved difficult to clearly convey the purpose and goals of the workshop to all the participants. This is actually not surprising considering the diversity of participants, their sheer number, and the fact that this was the first meeting of its kind and was different from the more traditional "information exchange" type of meeting.
10. The meeting benefited from having a large number of participants in that this increased the number and diversity of technical issues identified. This also provided a more technically impressive support group. However, the tradeoff was less effective communication and the need to divide the participants into smaller working groups which had to be conducted in parallel.
11. In their comments on the structure of the workshop, a great many people indicated that a major benefit was the free exchange of information and ideas that it promoted. Perhaps their major criticism was the need for more focus and structure. While this desire is appreciated, it is in some conflict with the concept of providing a free exchange of information. Too much structure would promote one-way communication from NASA to the participants. The intent was for the primary communication channel to be the other way. Providing the right structure and focus is a delicate matter.
12. In addition to helping define the need for and scope of an experimental test program, the workshop also provided excellent input towards the definition of a NASA development plan for resolving micro-gravity two-phase flow and heat transfer issues.

6 CONCLUSIONS AND RECOMMENDATIONS

The workshop was successful in achieving its main objective of identifying a large number of technical issues relating to the design of two-phase systems for space applications. The principal concern expressed was the need for verified analytical tools that will allow an engineer to confidently design a system to a known degree of accuracy. New and improved materials, for such applications as thermal storage and as heat transfer fluids, were also identified as major needs. In addition to these research efforts, a number of specific hardware needs were identified which will require development

in the relatively near future. These include heat pumps, low weight radiators, advanced heat pipes, stability enhancement devices, high heat flux evaporators, and liquid/vapor separators.

A centralized source for reliable, up-to-date information on two-phase flow in a space environment would be of major benefit to the technical community. A limited amount of micro-gravity information is available, but many researchers and designers are unaware of its existence.

Notwithstanding the currently available information, numerous issues remain. The great majority of designers will not trust the existing models until they have been verified with data from tests in micro-, partial, and/or artificial gravity fields. A variety of fluids also needs to be tested. This implies the need for a coordinated test program that will collect the appropriate information in a logical and efficient fashion. Section 7 discusses a recommended test program in detail.

The workshop participants indicated that they found the gathering to be a useful opportunity to discuss a complex and important subject. This is underscored by the fact that over two-thirds of those invited attended. In concert with the overwhelming majority of the participants, it is recommended that another workshop be held in approximately one year. However, this and any other future workshops should be structured somewhat differently and have fewer participants. Before the next workshop, a coherent test plan will have been formulated. The details of how to best implement this plan would be a suitable focus for this next workshop.

7 RECOMMENDED EXPERIMENTAL TEST PROGRAM

As is documented above, there are a number of significant issues relating to the design of two-phase systems for space applications. While a variety of earth-normal gravity mechanistic and empirical design tools (i.e., models) do exist, most research and design engineers believe that they have not been adequately validated for space applications. The general feeling is that it will be possible to develop satisfactory models, but more data is needed before they can be developed and accepted as credible.

In view of the above, it is recommended that a coordinated test program be established to generate the test data necessary to develop and validate the models. The tests performed should focus on the major design questions, as opposed to fundamental fluid mechanic and heat transfer issues. However, these two goals are not viewed as mutually exclusive; because of the rudimentary state of knowledge in the field, a significant amount of overlap is necessary. In addition, in order to minimize costs and expedite the testing process, as much testing as possible should be done using ground-based facilities

(e.g., up flow/down flow facilities, drop towers and reduced gravity aircraft). In general, a specific phenomenon should be researched only to the level necessary to obtain adequate resolution and experimental confidence.

The concept of a modular test fixture, which could be quickly reconfigured with substitute test articles, warrants serious consideration. Such a device would allow the relatively rapid changeout of, for example, an evaporator of one design for an evaporator of another. Alternately, different control concepts might be tested. In view of the different types of issues to be resolved (e.g., adiabatic flow, fluid positioning, etc.) several different test fixtures will probably be required. These should be as generic as possible, and, ideally, suitable for either drop tower, aircraft, or Shuttle testing. However, the cost, design requirements, and scheduling issues associated with flight hardware may make this goal impractical.

The test program and associated mechanistic/empirical design tool development will be an iterative process. Each set of tests will provide data that will improve upon the existing design tools. The knowledge gained in one set of testing will help determine the design and objectives of the next test set. This process will continue until it can be demonstrated that the latest available design tools provide adequate resolution for the major issues of concern.

Below is a basic outline of the recommended test program.

1. Perform a literature search and contact the leading researchers in the field to determine the state-of-the-art in understanding of two-phase phenomena in a space environment. The workshop itself provided a significant amount of information as to ongoing research efforts, but an orderly search is needed to insure completeness. At the workshop, it was interesting to note the disparity in awareness of the state-of-the-art between the participants.
2. Establish a data base that is accessible and useful to designers and researchers. This data base would include not only actual micro-gravity and related partial/normal gravity data, but would also include fundamental, mechanistic, and empirical models. It appears that somewhat more information is already available than many designers are aware of. The consolidation of this information into a single data base would thus be a major step forward in enhancing its usefulness. In addition, this effort would greatly help in the identification and quantification of missing information.
3. Identify, categorize, and rank the major design issues involved with two-phase systems. The workshop provided the major input to this task and should suffice for the preliminary test plan.

4. Determine the types and levels of testing needed to answer the major issues identified above. This need not be a detailed definition of specific tests, but rather a more generic description of the class of test or tests required to resolve certain questions.
5. Identify and/or develop mechanistic and empirical models to describe the physical phenomena of interest. These models should focus on the major design concerns and be based on the best available data. In addition, they should have the potential to evolve over time with improved data into design tools which will have widespread credibility.
6. Define a multifaceted test program to achieve the following objectives:
 - a) Improve the current state-of-knowledge.
 - b) Develop and improve the usefulness of existing mechanistic and empirical design tools, especially for micro-gravity applications.
 - c) Identify and develop missing knowledge.

The test program should be a multifaceted effort consisting of several interrelated elements, the exact definition of which is to be determined. The basic idea is to perform a series of tests which address the major questions in as concise a manner as possible without losing precision. It must be recognized that there is an inevitable compromise (the nature of which is to be determined) between i) the number and type of tests performed, ii) the physical phenomena investigated, iii) the level of detail and resolution sought, iv) cost, and v) manifesting.

This test program should incorporate, to the maximum extent possible, the two-phase testing efforts currently planned or proposed. To minimize costs and avoid manifesting problems it should also employ ground-based testing whenever possible. Where feasible, it may also involve "piggybacking" two-phase experiments with each other or with other related experiments or payloads.

7. Design and fabricate the modular test beds to address the major design issues. In parallel with this effort, the first set of specific experiments should be selected and the test hardware designed and fabricated. The experiments should then be mated to their respective test beds and the integrated assembly checked out.

8. Perform the first set of testing. Note that each test bed can follow its own test program. All tests need not be conducted serially.
9. Review the test results and then modify the test fixture or continue on to another test as appropriate. Depending on the objectives and results of a specific test, it may be desirable to repeat it at the same testing level (e.g., up flow/down flow, drop tower, aircraft, or Shuttle), repeat it at a higher level, or move on to the investigation of a different phenomenon. All of this can only be determined once the test is done. Hence, the details of this test program will evolve over time with only the broad outline specified at the start. The test program must be conducted in an iterative fashion.
10. Incorporate the test results into the data base and update the models. Report the findings at conferences and through other means so that the two-phase design community is aware of the evolving state-of-the-art.

APPENDIX A

PARTICIPANT PROFILE AND COMMENTS

The participants at the workshop came from a variety of backgrounds and work areas. In an effort to provide better perspective for their inputs, they were each asked to complete a profile form. The form asked each person for his or her organizational affiliation, principal work area, and technical specialty. The resulting profiles are shown in the accompanying figures (A1-A3). As seen in the figures, the workshop was attended by people from a wide range of organizations encompassing NASA, the national laboratories, academia, and private industry. Over half of the participants listed "thermal control and fluids management" as their principal work area. Two-thirds of the participants said that their technical specialty was "basic or applied research."

Each participant was also asked to complete a questionnaire which asked what the strong and weak points of the workshop were, how the workshop could be improved, and if more workshops should be held in the future.

In answer to the question, "What were the strong points of this workshop?", about half of the participants said that it was a good opportunity to meet with a diverse group of people to discuss this topic, and that all organizational areas were well represented. This was one of the few comments on which there was a large degree of consensus. A number of people also said that there was good circulation of information and that the workshop was a good opportunity for informal discussion. Some people said that the workshop provided a forum for prioritization of experimental issues. A few people pointed out that some of the working groups were well run.

Due to a high degree of overlap, the responses in the "What were the weak points?" section and the "How could we improve?" section have been combined. Comments in these two sections generally indicated a need for more direction on the expected role of the participants. A number of respondents suggested that the questions/issues be sent to

WORKSHOP PARTICIPANTS ORGANIZATIONAL AFFILIATION

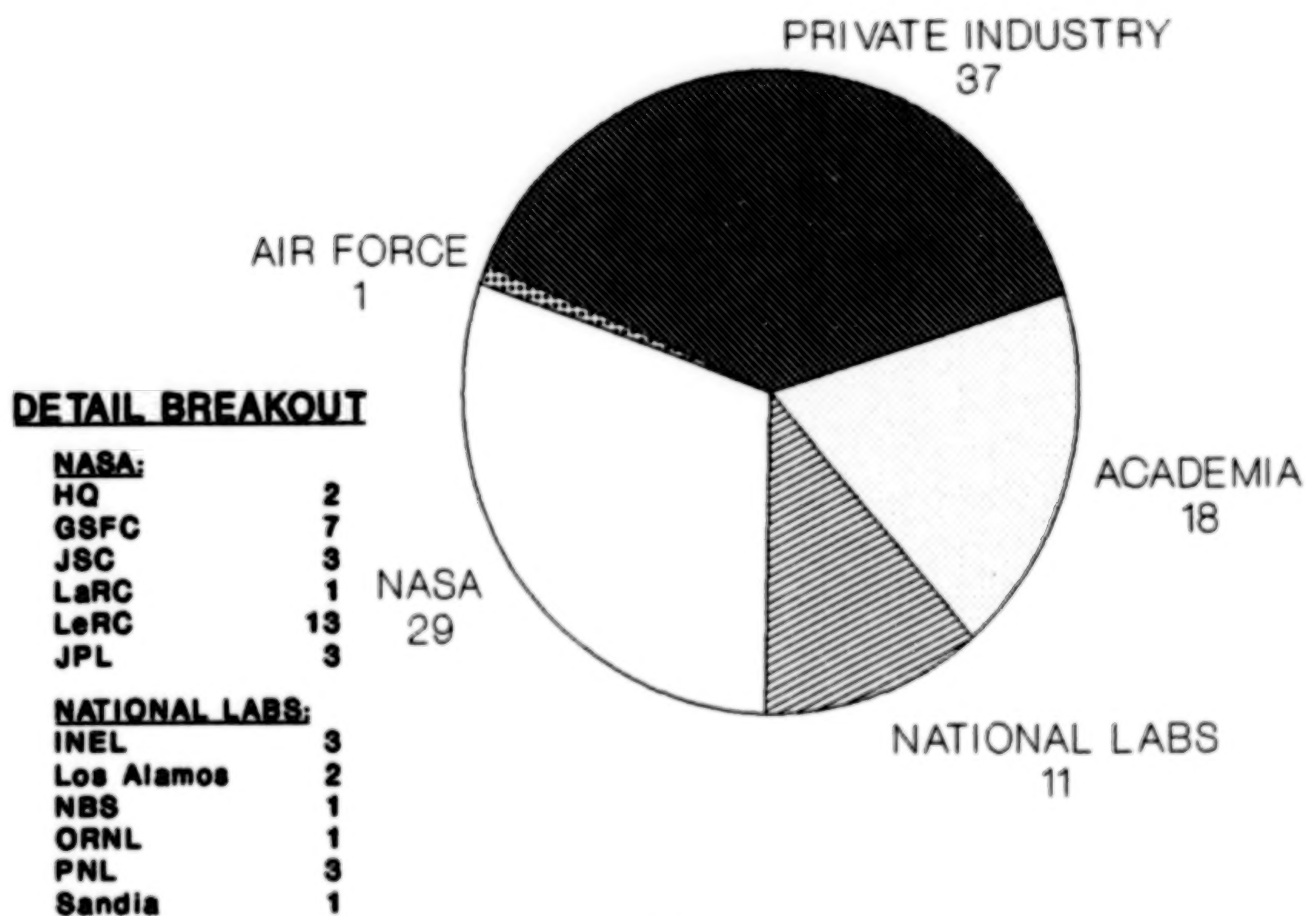


Figure A-1

WORKSHOP PARTICIPANTS

PRINCIPAL WORK AREA

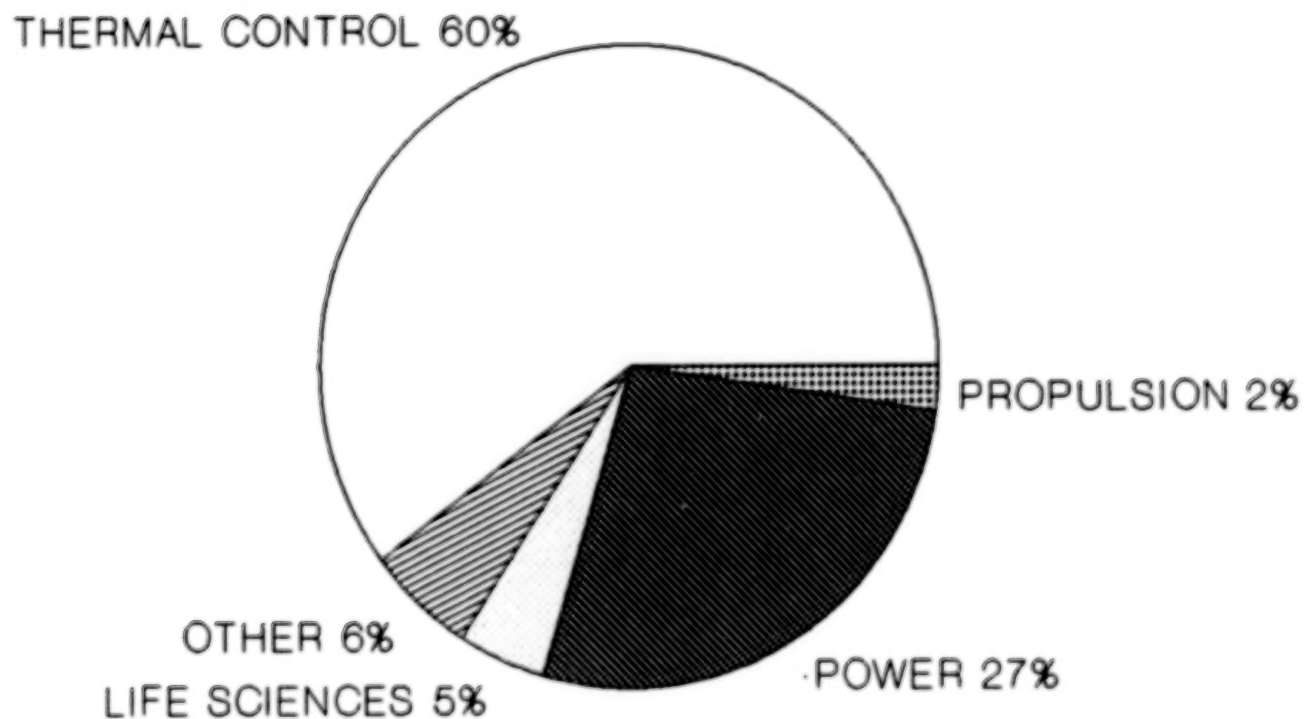


Figure A-2

WORKSHOP PARTICIPANTS TECHNICAL SPECIALTY

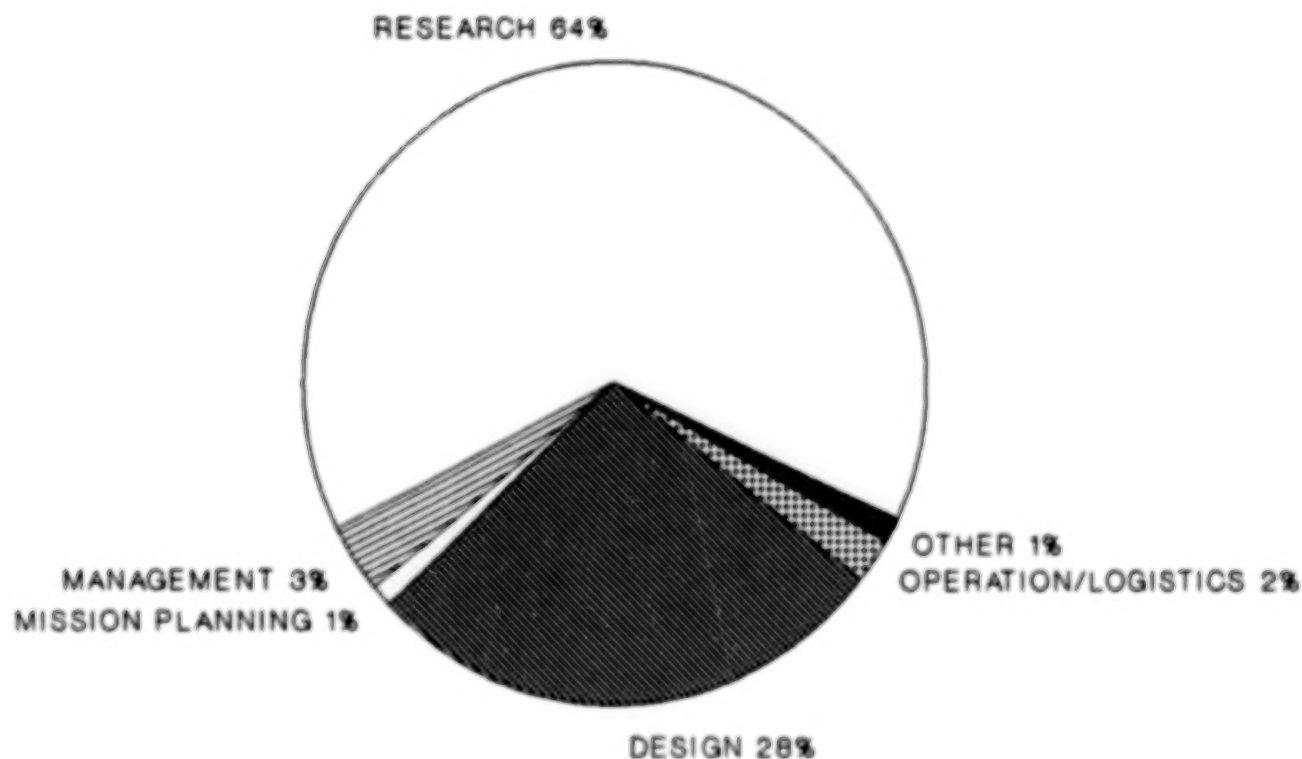


Figure A-3

the participants ahead of time. Along with this, several people suggested sending the technology issue input forms ahead of time. Many people indicated that they would have liked to have more direction once at the workshop. This includes presenting NASA long- and short-term goals, giving a background on prior flight tests, and then, at the start of each working group, stating the objectives and guidelines for the session. This would be facilitated by the use of a detailed agenda or strawman. Although some working group leaders adopted this approach, others did not.

There were several complaints about the presentations—that they were too long, that they weren't relevant to the topic being discussed, that they tended to focus the discussion on individual work rather than generic problems, and that they were sometimes pitches for an individual's research. Not surprisingly, some people requested fewer (or no) and shorter presentations. If there are presentations at future workshops, several people suggested that they should emphasize applied engineering rather than basic research.

Some respondents expressed concern that at times, the working groups lost focus and the discussions wandered. Although this is typical of many technical meetings, more preparation by the working group leaders might have reduced the problem.

There was a group of comments about who should or should not have attended the workshop. In general, the feeling was that there were too many people, that the groups were too large, and that there were not enough designers present, particularly in the area of propulsion.

There were many diverse comments on the structure of the workshop and what could have been different. The most prevalent comment was that the sessions should have been staggered, so that an individual could have attended all of the sessions that were of interest. This seems to necessitate a longer workshop, so that all areas can be covered. Even in the current format, quite a few people thought that there was not enough time. Several people also noted that the discussions were facilitated by a conference-style chair setup—as opposed to the classroom style used in some working groups.

Of the people that answered the question regarding future workshops, almost all said that more workshops of this type should be held. However, many of the yes respondents and one person who answered no said that the workshops should be smaller. For those that gave a time frame for the workshops, most said to hold them once a year, but the times went from every 6 months to every few years.

In summary, the workshop was thought to be a useful gathering of a diverse group of people to discuss a complex and important issue. Most of the participants would like to see additional workshops held, approximately once a year, albeit with fewer people and more direction.

APPENDIX B

DETAILED LISTING OF TECHNICAL ISSUES

FROM FORMS COMPLETED BY CONFERENCE PARTICIPANTS

One hundred forty-seven issue sheets were collected at the workshop, encompassing a wide variety of technical issues. For ease in listing, these issues have been divided into four categories, as follows:

- I. Global issues—these issues apply to more than one of the topics discussed at the workshop.
- II. Component-specific issues—these issues are unique to a specific component, but the components could be common to a number of systems. Components include reservoirs, evaporators, condensers, and radiators.
- III. System-specific issues—these involve complete systems which may be used by one or more disciplines.
- IV. Discipline-specific issues—discipline issues are unique to one particular subsystem, where the subsystems are: power, propulsion, and thermal control. Thermal control is further divided into instruments and life support.

In addition to listing issues, a number of conceptual definitions of possible experiments were given on the issue sheets. These are listed, following the same outline, after the issue list.

The following issues were identified:

I. GLOBAL ISSUES

A. Basic Issues

1. Need information on two-phase flow behavior in a variety of gravities.

| | |
|------------------------|--|
| Information needed: | pressure drops, heat transfer coefficient, critical heat flux, effect of non-condensable gases, void formation, and instabilities. |
| Gravity levels: | micro-gravity, 0.2- to 0.6-g, >1-g. |
| Conditions and events: | uniform heating, non-uniform heating, boiling, condensing, with Coriolis force, thin film, transients, steady state. |
| Fluids: | miscellaneous two-phase fluids, mixtures, liquid metals, fluids other than water or freon. |
| Configurations: | tubes, bends, valves, fittings, reducers and expanders, tube bundles. |
| Results required: | flow regime maps, correlations, computer codes. |
| Type of tests to run: | Drop tower, aircraft, Shuttle. |

2. Need to be able to assure phase separation when required in thermal and power systems.
3. Need to control interface position in tanks and reservoirs.
4. Need to be able to predict void formation during freeze/thaw cycling in heat pipes and thermal storage materials. Also need to predict effect of voids on heat transfer characteristics.
5. Need to locate suitable materials and identify materials properties for: heat pipe working fluids, life support working fluids, thermal storage materials, magnetic heat pumps, absorption heat pumps, and liquid metals above 60 psi. Mixtures need to be examined for use as life support working fluids.
6. Better computer codes are needed in all disciplines. This includes codes to predict void locations in phase change materials, modeling of heat pumps, heat pipe design algorithms and steady state/transient modeling, liquid metal heat pipe design correlations, radiator models, and propulsion system design tools.

7. Instability and transient effects need to be studied. This includes the effect of fluid instabilities on structural loading. Transient effects mainly refer to rapid changes in energy input in thermal systems.

B. Instrumentation

1. Develop sensor to determine evaporator demand in thermal cooling systems.
2. Develop quality sensor for two-phase systems.

C. Implementation

1. Investigate/design for long-term operation.
2. Establish a data base on two-phase technology.

II. COMPONENT-SPECIFIC ISSUES

A. Reservoirs

1. Study fluid management in two-phase reservoirs. Also need to investigate reservoir's ability to handle large changes in system volume and accompanying response time.
2. Look at sloshing and inflow/outflow in reservoirs.

B. Evaporators

1. Develop high heat flux evaporators.
2. Study burnout in evaporators.
3. Study hysteresis in flow boiling heat transfer evaporator design.

C. Condensers

1. Study stability of shear controlled condensers.

D. Radiators

1. Develop radiators insensitive to low-g accelerations.
2. Develop liquid droplet radiator for 200-°C applications.
3. Develop ultra-lightweight radiator, near 1 kg/m², for low-temperature applications.

III. SYSTEM-SPECIFIC ISSUES

A. Heat Pipes

1. Obtain basic information on micro-gravity characteristics of medium-temperature and high-temperature heat pipes.
2. Determine zero-g radial heat flux limit in evaporators.
3. Study effect of micro-gravity or artificial gravity on heat pipe evaporator temperatures and transport.
4. Develop side-flow (sub-cooled artery) heat pipe.
5. Develop removable heat pipes for long-term operation.
6. Develop cryogenic heat pipes.
7. Investigate powdered metal sintered wick heat pipes, including transients.
8. Develop variable conductance liquid metal heat pipes.
9. Develop high-performance low/non-toxic heat pipes for operation in micro-gravity, artificial gravity, and on lunar and Mars surfaces.
10. Predict heat pipe startup from the frozen state and validate predictions with experimental results.

B. Heat Pumps

1. Investigate different heat pump cycles and compare to system applications.

C. Capillary Pump Loops

1. Further characterize transient operation.
2. Determine acceleration impact on CPL systems.
3. Determine pressure drops vs. flow rate and power density in CPL systems.

IV. DISCIPLINE-SPECIFIC ISSUES

A. Power

1. Demonstrate appropriate sodium condensation and liquid transport strategies that can be incorporated in AMTEC systems.

2. Na/S battery and AMTEC.
3. Demonstrate Solar Stirling engine performance in a space environment.
4. Demonstrate closed cycle gas turbine operation in a space environment.

B. Propulsion

1. Study transfer line chill-down—cryogenic.
2. Study low-g, two-phase heat transfer characteristics applicable to the tank heat exchangers for a thermodynamic vent system for long-term cryogen storage.
3. Study forced convection, condensation, mixing, and bubble formation in receiving tank during non-vent transfer.

C. Thermal control, life support

1. Define toxic/non-toxic as it applies to life support systems.
2. Determine life support fluid operating temperature range.

That concludes the listing of the issues described on the technology issue sheets. A number of respondents suggested possible flight experiments to address the issues listed. The experiments suggested are listed below following the same outline that was used in the issue descriptions above.

I. GLOBAL ISSUES

A. Basic issues

1. Separators/Accumulators

- (a) KC-135 testing of SP-100 type of gas separator/accumulator with water and air.
- (b) On-orbit demonstration of lithium-helium separation.

2. Phase Change Materials

- (a) Need micro-gravity experience with phase change materials.
- (b) Multiple KC-135 tests of void formation in phase change materials.

3. Conduct a study for selecting working fluids for absorption heat pumps. Conduct experiments on earth, then test the most promising fluid in a flight experiment.

B. Instrumentation

1. Measurement of evaporator demand in CPL system—KC-135 experiment.

II. COMPONENT-SPECIFIC ISSUES

A. Reservoirs

1. Two-phase accumulator transient tests.
2. System-level transient tests of flowrate control.
3. Flight tests of alternative reservoir concepts.

B. Radiators

1. Construct dual-slot radiator element for 'SHARE'-type flight experiment to confirm thermal performance in zero-g.
2. Small bubble membrane radiator experiment.
3. Liquid droplet radiator flight test

III. SYSTEM-SPECIFIC ISSUES

A. Heat Pipes

1. Experiment at low-g or micro-g to allow one to observe the thermophysics of the wick and the wick-liquid-vapor region.
2. Fabricate and test side-flow heat pipes for Shuttle testing.
3. (a) Test in zero-g of cryogenic heat pipes with sintered powder metal wicks and boiling tolerant arteries.
(b) Fabricate and test liquid nitrogen or liquid oxygen axial groove heat pipe as Hitchhiker experiment. Test various heat input lengths and operating temperatures. Test startup from supercritical state.
(c) Cryo-refrigerator cooled cryogenic heat pipe test.

4. Experiment to ascertain 0-g effect on physical properties—surface tension, wettability, contact angle, etc.—for liquid metal/water heat pipes.

IV. DISCIPLINE-SPECIFIC ISSUES

A. Power

1. AMTEC sodium condensation and liquid transport experiment.

B. Propulsion

1. Test of no-vent fill of tanks.
2. Transfer line chill experiments in low gravity.

C. Thermal control, life support

1. Flight test a boiling tolerant sintered powder metal artery heat pipe using an acceptable working fluid (water/acetone/ethanol).

APPENDIX C
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Report Documentation Page

| | | | | | |
|--|--|---|---|--|-----------------------------|
| 1. Report No. NASA CP-3043 | | 2. Government Accession No. | | 3. Recipient's Catalog No. | |
| 4. Title and Subtitle Workshop on Two-Phase Fluid Behavior in a Space Environment | | | | 5. Report Date July 1989 | |
| | | | | 6. Performing Organization Code 732.0 | |
| 7. Author(s) Theodore D. Swanson, Al Juhasz, W. Russ Long, and Laura Ottenstein, Editors | | | | 8. Performing Organization Report No. 89B00114 | |
| | | | | 10. Work Unit No. N/A | |
| 9. Performing Organization Name and Address Goddard Space Flight Center Greenbelt, Maryland 20771 | | | | 11. Contract or Grant No. | |
| | | | | 13. Type of Report and Period Covered Conference Publication | |
| 12. Sponsoring Agency Name and Address Office of Aeronautics and Space Technology National Aeronautics and Space Administration Washington, D.C. 20546-0001 | | | | 14. Sponsoring Agency Code | |
| | | | | | |
| 15. Supplementary Notes Al Juhasz--NASA/Lewis Research Center, Cleveland, Ohio; W. Russ Long--NASA/Johnson Space Center, Houston, Texas; Theodore D. Swanson and Laura Ottenstein--NASA/Goddard Space Flight Center, Greenbelt, Maryland. | | | | | |
| 16. Abstract <p>The Workshop was successful in achieving its main objective of identifying a large number of technical issues relating to the design of two-phase systems for space applications. The principal concern expressed was the need for verified analytical tools that will allow an engineer to confidently design a system to a known degree of accuracy. New and improved materials, for such applications as thermal storage and as heat transfer fluids, were also identified as major needs. In addition to these research efforts, a number of specific hardware needs were identified which will require development in the relatively near future. These include heat pumps, low weight radiators, advanced heat pipes, stability enhancement devices, high heat flux evaporators, and liquid/vapor separators. Also identified was the need for a centralized source of reliable, up-to-date information on two-phase flow in a space environment.</p> | | | | | |
| 17. Key Words (Suggested by Author(s)) Boiling, Flow, Fluid Heat Transfer, Gas Heat Transfer, Heat Transfer, Heat Pipes, Heat Pumps, Radiators | | | 18. Distribution Statement Unclassified - Unlimited Subject Category 34 | | |
| 19. Security Classif. (of this report) Unclassified | | 20. Security Classif. (of this page) Unclassified | | 21. No. of pages 48 | 22. Price A03 |

National Aeronautics and
Space Administration
Code NTT-4

Washington, D.C.
20546-0001

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